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Evolution of Stellar Magnetic Fields

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Abstract. Stellar magnetic fields can reliably be characterized by several magnetic activity indicators, such as X-ray or radio luminosity. Physical processes leading to such emission provide important information on dynamic processes in stellar atmospheres and magnetic structuring.

Keywords. Stars: activity, stars: coronae, stars: flare, stars: magnetic fields

1. Introduction

Stellar magnetic activity relies on "surface" magnetic fields expanding into the chromosphere and corona. Although methods have been developed to measure such fields (e.g., Zeeman line splitting resp. broadening, polarization, frequency analysis of coherent radio maser emission, models for gyrosynchrotron radio radiation), they remain challenging, with intricate problems making accurate measurements even of the average magnetic flux density ambiguous. Activity indicators such as Hα, Ca II, UV lines, or extreme ultraviolet, X-ray, and non-thermal radio fluxes are easier to measure for large samples of stars. How representative are they? Pevtsov *et al.* (2003) found a nearly linear correlation between total (unsigned) magnetic flux and X-ray luminosity of various solar features and the full-disk solar and stellar values, suggesting not only that L_X serves as a good proxy for magnetic flux but also that stellar activity relies on solar-like magnetic features.

2. Long-Term Evolution of Magnetic Activity

A similar analogy between activity and magnetic flux is seen in diagrams displaying these quantities as a function of rotation period P or Rossby number. The now well established trends of increasing L_X with decreasing P (approx. $L_X \propto P^{-2}$, Pizzolato *et al.* 2003) plus saturation at $L_X/L_{\rm bol} \approx 10^{-3}$ for the fastest rotators are mirrored in similar trends for the average surface magnetic flux $< Bf >$ notwithstanding complications in Zeeman broadening measurements involved here (Reiners 2012).

This then suggests L_X (or L_{UV}) measurements as convenient proxies for the long-term evolution of magnetic flux. For solar analogs, cluster and field star studies show a systematic decrease of L_X with age, approximately like $\propto t^{-1.5}$, accompanied by a decrease of average coronal temperature from about 10 MK for very young solar analogs to 2 MK for the present Sun (Güdel *et al.* 1997). Similar trends are found for non-thermal radio emission although the decaying trend seems to be steeper, while trends in the ultraviolet are more moderate (Ribas *et al.* 2005, Güdel 2004).

3. Magnetic Activity: Minimum States

How low, then, can magnetic activity go? Schröder *et al.* (2012) found the extremely low solar Ca II S index in 2009 comparable to "Maunder minimum" stars, and further suggested that magnetic heating is insufficient for chromospheres during such times while

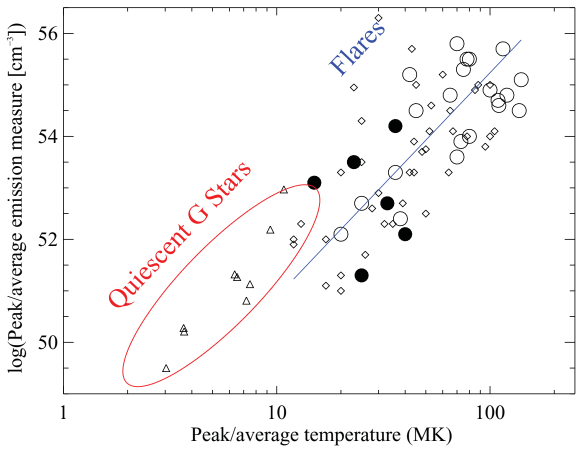

Figure 1. Correlation between peak/average emission measure and peak/average temperature for coronal plasma during flares (circles)/quiescence (triangles in red area; Güdel 2004.)

unproblematic for the weak X-ray emission. The low L_X in that episode (Sylwester *et al.* 2012) is comparable to or lower than the X-ray weakest main-sequence stars (Schmitt 1997). Magnetic activity does not disappear during a cool star's main-sequence lifetime.

4. Magnetic Activity: High Activity and Flaring

The other extreme of magnetic activity found in magnetically active stars is reminiscent of solar/stellar flares: high-temperature plasma, variability, non-thermal radio emission, and in particular a correlation between total luminosity (resp. flare luminosity) and average electron temperature (Fig. 1). This latter coincidence (Güdel 2004) may suggest that a large number of continuously occurring flares are at the origin of the continuous X-ray emission of active stars. This idea gets support from flare statistics (occurrence rate vs. flare energy) indicating that the sum of numerous, weak flares dominates the X-ray radiative output from active coronae (Audard *et al.* 2000). A "micro-flaring" corona would make all concepts of static coronal magnetic structures obsolete and introduce a dynamic magnetic atmosphere, with continuous mass flows, reconnection events, particle acceleration and frequent episodic heating keeping the corona at high temperatures.

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